NUCLEAR SCIENCE AND TECHNIQUES **26**, 060102 (2015)

# The waveguide system of the HLS 800 MeV Linac*

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(Received February 13, 2015; accepted in revised form March 29, 2015; published online December 20, 2015)

To upgrade Hefei Light Source (HLS) Linac, eight accelerating units have been constructed to realize full-energy injection of the storage ring. Each of the units consists of two 3-m accelerators driven by one klystron. The input cavity detuning method was developed to measure and correct the phase length of the RF power distribution waveguide system. The design of the waveguide network and the principles of the detuning method are presented in this paper. After correction, the phase error between the waveguide of the two accelerators was less than $\pm 0.5°$, and the maximum electron energy of Linac reached 805 MeV, which is very near the theoretical maximum value of 810 MeV. These results demonstrate that the calibration of the waveguide was successful.

Keywords: Linac, Waveguide, Phase length

DOI: 10.13538/j.1001-8042/nst.26.060102



## I. HLS 800 MEV LINAC

The 800 MeV Linac [1–6] layout is shown in Fig. 1. The accelerating system consists of one prebuncher (a single standing-wave cavity), one buncher (a 1 m traveling-wave accelerating construct), and eight accelerating units (each composed of two 3-m constant-gradient traveling-wave accelerators) that are driven by eight klystrons. Klystron No. 1 and No. 8 are 80 MW, whereas the others are 50 MW. The RF SLAC energy doubler (SLED) [7–12] is installed in a 50 MW station. When all of the SLEDs are working, the electron beam energy can reach 1 GeV [13, 14]. The main parameters of the 800 MeV Linac are listed in Table 1.

TABLE 1. Parameters of the 800 MeV Linac

| Parameters | Values |
|---|---|
| Operating frequency ($f$) | 2856 MHz |
| Phase shift per cavity | $2\pi/3$ |
| Range of the shunt impedance ($R_s$) | 55–63 MΩ/m |
| Normalized group velocity range ($V_g/c$) | 0.0177–0.0063 |
| Attenuation parameter ($\tau$) | 0.585 Np |
| Filling time ($t_F$ ) | 0.8995 µs |
| Operating state | 42 °C, vacuum |
| No. of standard 3-m sections | 16 |
| No. of cavities in each 3-m section | 86 + 2 coupler |
| Distance between the inputs of two consecutive sections | 31λ |
| No. of 6-m accelerator units | 8 |

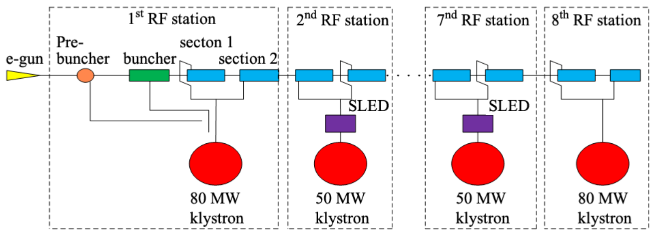


Fig. 1. (Color online) The 800 MeV Linac layout.

## II. DESIGN OF THE WAVEGUIDE NETWORK

In the case of one klystron driving two accelerators, a 3-dB power splitter and a phase-balance waveguide network should be employed for power distribution. The arrangement of the waveguide network is shown in Fig. 2. Branch A starts from the pass-thru port of the splitter, which is connected to one accelerating section (A) directly, whereas branch B starts from the coupling port, which is connected to the opposite side of the successive section (B). The horizontal span between the two branches is 31λ, which is equal to the distance between the two accelerator input ports. The eight accelerating units are arranged in the sequence AB, BA, . . . .

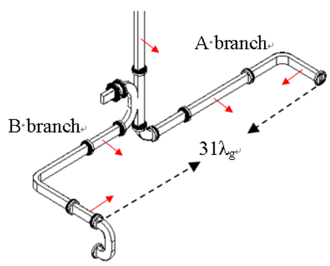


Fig. 2. (Color online) The waveguide network.

To obtain a phase balance between branches A and B, the geometrical phase lengths of the waveguides must be calcu-

* Supported by National Natural Science Foundation of China (No. 11079034)

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lated, and the phase change caused by some physical characteristics of the components must also be considered. In the network shown in Fig. 2, the coupling port of the 3-dB splitter lags 90° behind the pass-thru. A phase difference of 180° exists between the E-plane right-bend waveguide and the left-bend waveguide [15]. The change in the direction of the electric field along the E-bend waveguide is marked in Fig. 2.

The calculated phase lengths of branch A and B are $15.4368\lambda_g$ and $15.6836\lambda_g$, respectively, where $\lambda_g$ is the waveguide wavelength.

At the power splitter, the phase length of branch B physically increases by $0.25\lambda_g$.

The total phase length of branch B is $0.4968\lambda_g$ longer than that of branch A, which exactly offsets the phase difference of the E-bend waveguides.

## III. PHASE LENGTH MEASURING METHOD

A reflection phase measuring method based on shorting the accelerator output coupler is normally used to measure the waveguide phase length [16–18]. As shown in Fig. 3, the output coupler of accelerator A is terminated by the short, and accelerator B is matched with the load. A network analyzer that is connected to the 3-dB splitter input port measures the S11 parameters of the signal reflected by branch A. The difference between the phase shift of the accelerator section and the reflection signal phase is the phase length of branch A. By exchanging the short and the load, a measurement of the phase length of branch B can be performed [19].

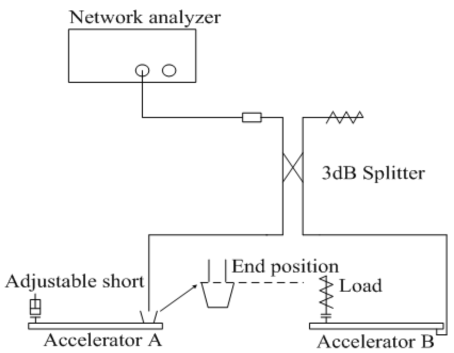


Fig. 3. Reflection method for phase length measurement.

The waveguide phase length can also be determined by the measurement of transmission parameters. In the measurement, the accelerator output signal is fed back to the network analyzer. For this purpose, a couple of coaxial-waveguide adapters are needed. It is very important to ensure that their connector directions are uniformly aligned with the waveguide. A reversed connection would cause a 180° phase shift. The change in the electric field in in-phase and anti-phase connections are shown in Fig. 4.

A disadvantage of the transmission method is that the coaxial cable is too long to maintain phase stability when the measurement switches from branch A to B.

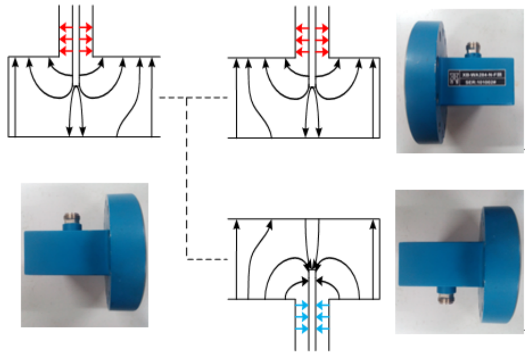

Fig. 4. (Color online) In-phase and anti-phase connection of coaxial-waveguide adapters.

The reflection and transmission methods suffer from the following problems:

1) Temperature stability is critical. The accelerator's phase shift, which is significantly affected by temperature variations, is included in the measurement result. Normally, the accelerator temperature variation should be maintained within ±0.5 °C during the phase measurement.

2) The phase length of the waveguide network is measured from the start of the network to the input port of the coupler end position, as seen in Fig. 3. The phase length of the coupler is not included. Therefore, even if the waveguide branches are perfectly in phase, the electron beam will still be in different accelerating phases when it passes through the two accelerators if the couplers have phase errors.

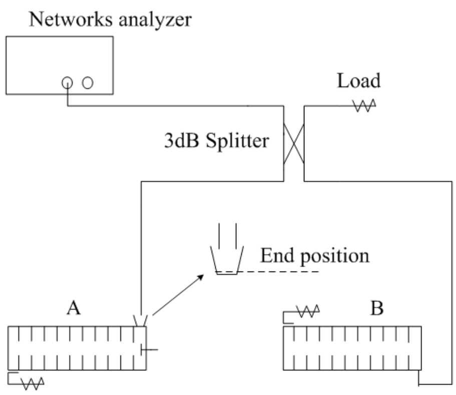


Fig. 5. Input-cavity detuning method.

The modified reflection method is applied in the 800 MeV Linac waveguide phase measurement. In this method, the reflection does not occur at the output, but rather at the input, of the accelerator. As shown in Fig. 5, a copper stick is inserted from the beam entrance into the first cavity of accelerator A. The cavity is detuned completely, and total reflection occurs. The equivalent reflecting plane is very close to the cavity surface (the end position is labeled in Fig. 5). Therefore, the input coupler is included in the waveguide network.

This method has good temperature tolerance. The total reflection of detuned accelerator A is not affected by temper-

ature variations. Because the input bandwidth of the accelerator is approximately ±1 MHz, and the resonance frequency shift with temperature is 50 kHz/°C, no reflection occurs in accelerator B and interferes the phase measurement of branch A if the temperature variation is less than ±5 °C.

To measure the phase length of branch B, the only action that must be performed is to remove the stick from accelerator A and then insert it into accelerator B. No RF component is removed or re-installed and no accidental error due to mechanical problems can occur.

## IV. MEASUREMENT AND CALIBRATION OF THE WAVEGUIDE NETWORK

Figure 6 shows a picture of the 800 MeV Linac. One accelerating unit in an AB arrangement is shown in Fig. 7. The RF characteristics of the eight accelerating units were checked after, and the voltage standing wave ratio (VSWR) on the splitter input was less than 1.05, which demonstrates that the installation was successful. Then, the measuring and correcting of the waveguide network phase lengths began. As shown in Fig. 8, a copper stick was used to detune the input cavity, and a special clamper was used to deform the waveguide wall and adjust the phase. The results of the phase measurement (before and after adjustment) are listed in Table 2. Note that the deviation between the two branches was less than ±0.5° after correction.

Fig. 6. (Color online) The picture of the 800 MeV Linac.

When the Linac was operational, the electron beam energy was measured. The maximal energy reached 805 MeV. Thus, the deviation from the theoretical maximum value of 810 MeV was approximately 0.6%. Assuming that the energy difference is completely caused by the waveguide phase errors, the average phase error of the eight units is only 0.7°. This result demonstrates that phase measurement and correction are reliable.

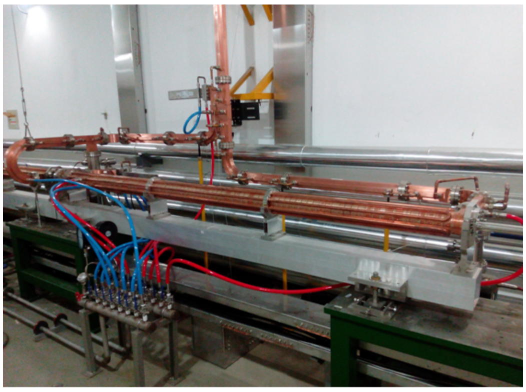

Fig. 7. (Color online) An accelerating unit in the AB arrangement.

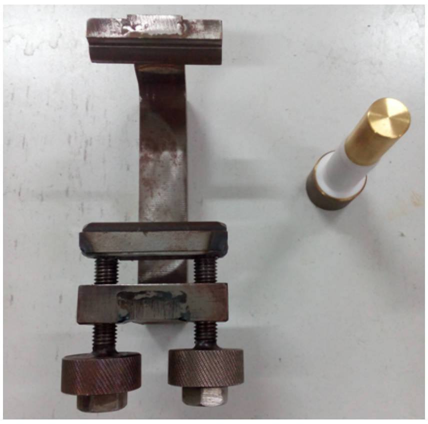

Fig. 8. (Color online) The clamper for phase adjustment and copper stick for cavity detuning.

TABLE 2. Phase length measurement results

| Accelerator unit | | Phase length (degrees) | |
|---|---|---|---|
| No. | | Initial | Adjusted |
| 1# | A | −17.5 | 10.6 |
| | B | 9.0 | 10.1 |
| 2# | B | 160.6 | 161.4 |
| | A | 141.3 | 161.1 |
| 3# | A | 95.5 | 113.4 |
| | B | 111.5 | 113.3 |
| 4# | B | 126.8 | 126.8 |
| | A | 103.6 | 127 |
| 5# | A | 120.9 | 126.8 |
| | B | 126.6 | 126.7 |
| 6# | B | 142.0 | 143.8 |
| | A | 117.8 | 144.0 |
| 7# | A | 135.6 | 158.0 |
| | B | 156.6 | 157.6 |
| 8# | B | −50.0 | −50.0 |
| | A | −73.1 | −50.0 |

## V. CONCLUSION

An input cavity detuning method has been applied to successfully measure and correct the phase length of the waveg-

uide network in the HLS 800 MeV Linac. Compared with traditional methods, the proposed detuning method is more convenient because it does not require any waveguide or coaxial component to be removed or assembled during the phasing process. It is also more reliable because there is no possibility of accidental errors due to mechanical problems or unstable temperature. Finally, it is more accurate because the input coupler's phase error can be corrected.


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